

An exact integral relation between the ^{56}Ni mass and the bolometric light curve of a type Ia supernova

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The mass of ^{56}Ni that is formed at the onset of a type Ia supernova is an essential parameter in its modeling. Significant effort has been invested in deriving approximate relations between the light curves and this mass (e.g. [1–5]). An exact relation between the ^{56}Ni mass and the bolometric light curve can be derived as follows, using the following excellent approximations: 1. the emission is powered solely by $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$; 2. each mass element propagates at a non-relativistic velocity which is constant in time (free coasting); and 3. the internal energy is dominated by radiation. Under these approximations, the energy $E(t)$ carried by radiation in the ejecta satisfies:

$$dE/dt = -E(t)/t - L_{\text{bol}}(t) + Q(t), \quad (1)$$

where $Q(t) = Q_{\text{Ni}}M_{\text{Ni}}(t)/\tau_{\text{Ni}} + Q_{\text{Co}}M_{\text{Co}}(t)/\tau_{\text{Co}}$ is the deposition of energy by the decay which is precisely known. Multiplying this relation by t and integrating over time we find: $E(t) \cdot t = \int_0^t Q(t') t' dt' - \int_0^t L_{\text{bol}}(t') t' dt'$. At late times, $t \gg t_{\text{peak}}$, the energy inside the ejecta decreases rapidly due to its escape, and thus we have

$$\int_0^t Q(t') t' dt' = \int_0^t L_{\text{bol}}(t') t' dt' \quad \text{at } t \gg t_{\text{peak}}. \quad (2)$$

The right hand side of eq. (2) is an observable while the left hand side is a known function that is proportional to the mass of ^{56}Ni formed at the explosion. We emphasize that this relation is correct regardless of the opacities, density distribution or ^{56}Ni deposition distribution in the ejecta and is very different from “Arnett’s rule”, $L_{\text{peak}} \sim Q(t_{\text{peak}})$ [2, 4]. By comparing $\int_0^t Q(t') t' dt'$ with $\int_0^t L_{\text{bol}}(t') t' dt'$ at $t \sim 40$ day after the explosion, the mass of ^{56}Ni can be found directly from UV, optical and infrared observations with modest corrections due to the unobserved gamma-rays and due to the small residual energy in the ejecta, $E(t) \cdot t > 0$.

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